
Title:

*Photonic Integrated Circuit (PIC) Device Structures:
Background, Fabrication Ecosystem, Relevance to Space Systems Applications, and Discussion
of Related Radiation Effects*

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BOK Executive Summary:

Electronic integrated circuits are considered one of the most significant technological advances of the 20th century, with demonstrated impact in their ability to incorporate successively higher numbers transistors and construct electronic devices onto a single CMOS chip. Photonic integrated circuits (PICs) exist as the optical analog to integrated circuits; however, in place of transistors, PICs consist of numerous scaled optical components, including such “building-block” structures as waveguides, MMIs, lasers, and optical ring resonators. The ability to construct electronic and photonic components on a single microsystems platform offers transformative potential for the development of technologies in fields including communications, biomedical device development, autonomous navigation, and chemical and atmospheric sensing. Developing on-chip systems that provide new avenues for integration and replacement of bulk optical and electro-optic components also reduces size, weight, power and cost (SWaP-C) limitations, which are important in the selection of instrumentation for specific flight projects. The number of applications currently emerging for complex photonics systems—particularly in data communications—warrants additional investigations when considering reliability for space systems development. This Body of Knowledge document seeks to provide an overview of existing integrated photonics architectures; the current state of design, development, and fabrication ecosystems in the United States and Europe; and potential space applications, with emphasis given to associated radiation effects and reliability.

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I. Background: Photonic Integrated Circuits

a. Background and Primary Advantages offered by Integrated Photonics

The invention of the transistor and subsequent advent of integrated circuits technology is widely considered to be one of the most significant discoveries of the 20th century. In 1958, the monolithic integrated circuit was developed at Texas Instruments to replace previous time-intensive methods of hand-soldering discrete elements¹. Since these initial innovations in the late 1950s and 1960s, the progress and development of semiconductor industries has experienced continued rapid growth, with Moore's Law describing a doubling in the number of transistors achievable on integrated circuits every two years. The idea of an optical equivalent to integrated electronic circuits—integrated optics—was first proposed by Stewart Miller of Bell Labs in 1969², who suggested that a “complex patterns of optical wave circuits, whose communication function might be somewhat analogous to that of lower frequency integrated circuits, could be fabricated in a sheet of dielectric using photolithographic techniques.”

The idea of using integrated photonics to scale multiple optical components on a single monolithic chip offers significant advantages for use in computing and communications systems. As bandwidth requirements continue to increase for communication amongst electronic devices in data centers, problems associated with loss, dispersion, and cross-talk become pronounced in conventional copper channels³. Initial interest in integrated photonics has been particularly concentrated on the realization of optical interconnects for data centers using vertical-cavity surface-emitting laser technologies⁴. Advantages pertaining to the use of photonics in communications systems include larger bandwidths than those achievable with electronic systems (on the order of 10-100 THz), minimal loss and electromagnetic interference, lower required powers, and potential improvements in security⁵.

Early advances in integrated photonics recognized that micron-scale waveguides could be fabricated using existing CMOS process, even with substantial differences in refractive indices of silicon and silicon dioxide required. The promise of scalable existing manufacturing techniques and the potential integration with silicon electronics motivated growth of commercial integrated photonics companies in the late 1990s and early 2000s⁶. Since this time, the development of integrated photonics circuits has been characterized by impressive demonstrations, such as the establishment of active on-chip components including amplifiers and lasers, and the development of robust 500 GB/s transmitter and receiver photonic integrated circuit modules⁷. The possible applications for photonic integrated circuits (PICs) using silicon and other materials platforms, such as compound semiconductors, extend beyond telecommunications for possible use in disposable high resolution biosensors, optical storage, displays, and sensing for navigation/positioning purposes. Early efforts to investigate the potential of integrated photonics for space-systems applications appear promising with respect to radiation hardness; to date, radiation tests of integrated photonics devices at anticipated dose levels for space missions have not affected device performance, for both silicon and indium phosphide material platforms.

b. Materials used in Integrated Photonics Devices

As with integrated electronic circuits, there have been long-standing debates whether to broadly develop manufacturing systems for photonic integrated circuits on silicon (Si), indium phosphide (InP), or

¹ R. Wlaer. (1992). *Silicon Destiny: The Story of Application Specific Integrated Circuits*. Milpitas: CMC Publications.

² S. Miller. (1969). “Integrated Optics: An Introduction.” *The Bell System: Technical Journal*, 48 (7), pp. 2059-2069.

³ S. Fathpour and B. Jalali. (2012). *Silicon Photonics for Telecommunications and Biomedicine*. Boca Raton: CRC Press.

⁴ R. Palmer. (2014). *Silicon Photonic Modulators for Low-Power Applications*. Karlsruhe: KIT Scientific Publishing.

⁵ A. Foster (2015). “Integrated Photonics.” Presentation, Johns Hopkins University, Department of Electrical and Computer Engineering.

⁶ C. Gunn and T. Koch. “Silicon Photonics.” *Optical Fiber Telecommunications VA: Components and Subsystems*. Burlington: Elsevier, Inc.

⁷ J. Pleumeekers, et. al (2014). “Manufacturing Profess for InP-based 500 Gb/s Photonic Integrated Circuits.” *CS Mantech Conference*. Available: <http://www.csmantech.org/Digests/2013/papers/007.pdf>

gallium arsenide (GaAs) materials platforms. Photonic integrated circuits have been fabricated on a wide variety of materials, ranging from standard element semiconductors and compound semiconductors to dielectric materials and nonlinear crystal materials⁸. Different types of materials possess specific physical properties that may make them more or less preferable for any given individual application in integrated optics. Examples may include the use of lithium niobate to fabricate low-loss waveguide devices⁹ or integrated flexible chalcogenide glass to make photonic crystals with mechanical flexibility¹⁰. However, to date, the largest financial investments that have been directed towards standardization of materials in fabrication ecosystems have been primarily focused on silicon and indium phosphide photonic integrated circuits.

The use of silicon (Si) for integrated photonics offers the advantage of existing mature CMOS fabrication technologies and compatibility with CMOS-based electronics. The ubiquitous use of CMOS technologies for integrated electronics means that existing fabrication capabilities can provide reliable, high-volume manufacturing techniques with exceptionally high levels of precision¹¹. As one of the most abundant elements on Earth, silicon may be used for the development of devices on-chip that are able to replace previous bulk functions and deliver improvements in both size and cost¹².

A broad array of on-chip optical components have been fabricated using silicon substrates, including a significant number of waveguide-based devices, such as individual channel waveguides, ring resonators, and Mach-Zehnder structures, which have then been assembled to produce more complex integrated photonic circuits¹³. Silicon waveguide structures are effective at guiding light at relevant telecommunications wavelengths, with current propagation losses less than 1 Db/cm. Additionally, Silicon structures can deliver tight mode confinement that allows for the use of efficient geometries without extensive bend losses. In addition to standard crystalline silicon, amorphous silicon has also been used in the fabrication of integrated photonic devices, and also provides low propagation loss¹⁴.

In contrast to devices fabricated on silicon, which has an indirect bandgap, one of the primary benefits of using indium phosphide is the ability to fabricate active optical components on chip. III-V semiconductors like InP have direct bandgaps, which means that they can efficiently absorb and emit photons that have energies in the range slightly above their individual bandgaps. The greater electron mobility of indium phosphide as compared to silicon may also allow for higher-power and higher-frequency applications relevant for optical communications¹⁵. The most well-established photonics foundry ecosystem in Europe is primarily based on the development of InP devices and has standardized fabrication processes for such active components as semiconductor optical amplifiers (SOAs) and distributed Bragg reflector (DBR) lasers¹⁶.

Ongoing research and development efforts continue to investigate a range of materials platforms for the development of photonic integrated circuits. In addition to the consideration of silicon and indium phosphide as separate monolithic materials platforms, heterogeneous integration of specific optical components has also been completed on-chip. Heterogeneous integration by direct wafer bonding of a III-V active region has been completed on pre-patterned silicon-on-insulator (SOA) waveguides. This

⁸ D. Liang and J. Bowers. (2009). "Photonic Integration: Si or InP substrates." *Electronics Letters*, 45 (12), pp. 578-581.

⁹ W. Sohler, et. al (2008). "Integrated Optical Devices in Lithium Niobate." *Optics and Photonics New*, 19 (1), pp. 24 – 31.

¹⁰ L. Li, et. al. (2014). "Integrated Flexible Chalcogenide Glass Photonic Devices." *Nature Photonics*, 8, pp. 643-649.

¹¹ J. Bowers (2016). "Silicon Photonics." Optoelectronics Research Group Web Page, Available: <http://optoelectronics.ece.ucsb.edu/>

¹² G.T. Reed. (2004). "Device Physics: The Optical Age of Silicon." *Nature*, 427, pp. 595-601.

¹³ L. Chrostowski and M. Hochberg (2015). *Silicon Photonics Design*. Cambridge: University Printing House.

¹⁴ J. Ahmed, et. al (2013). *Optical Signal Processing in Silicon Photonics*. New York: Springer.

¹⁵ B. Rogers, et. al (2015). *Nanotechnology: Understanding Small Systems*. Boca Raton: Taylor and Francis Group.

¹⁶ N. Androlli, et. al (2015). "InP Monolithically Integrated Coherent Transmitter." *Optics Express*, 23 (8).

technique has since been used to demonstrate numerous discrete active devices in conjunction with silicon based passive optical devices¹⁷.

c. Structural Building Blocks

Integrated photonics circuits consist of numerous scaled optical components incorporated on a single chip, with either monolithic or heterogeneous integration, dependent on materials selection. Unlike integrated electronic circuits, in which the fundamental building block is the transistor, a variety of different optical building block structures are used in integrated optics. The following is an abridged list of frequently implemented building blocks in PIC designs and a brief overview of their associated functions. PICs can contain both active and passive components, in which active building blocks involve dynamic interactions between the material platform and light, such as amplification¹⁸. Different fabrication services/ecosystems provide foundry-specific building blocks libraries with detailed descriptions of individual element parameters and restrictions on component functionality and integration¹⁹.

i. Sample Building Block Components

• Waveguides:

Integrated photonics structures known as waveguides are the simplest available structures for guiding light and interconnecting different elements on an optical chip. These optical waveguides are created to confine light by fabricating a specific waveguide structure on a layer of low refractive index material, such that the light is guided through the process of total internal reflection (e.g. for silicon integrated photonics structures, a layer of silicon dioxide is used). A variety of fabrication techniques exist for integrated photonics waveguides based on the intended material used for the photonic integrated circuit: channel waveguides on semiconductor and crystal materials are typically fabricated using conventional lithographic methods and some form of epitaxy, waveguides in transparent glasses may be fabricated using pulsed laser beams, etc²⁰. The selected material platform dictates the design rules for waveguide structures, limiting specifications such as a waveguide bend radius. Different fabrication techniques may be designed to optimize specific waveguide parameters subject to the application of interest, including the index contrast, operational wavelength-needed for the intended application, and input/output losses.

Many forms of channel waveguide geometries have been developed to optimize different parameters; the most common structures for silicon photonics are the buried channel, strip, and rib waveguides²¹. The following schematic details the range of waveguide structures implemented in integrated photonics devices:

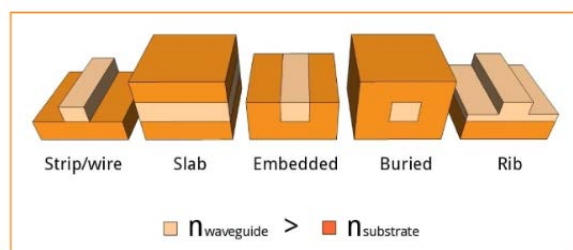


Figure 2.1: Common waveguide building block geometries for PIC-devices²²

¹⁷ M. Heck and J.E. Bowers. "Hybrid and Heterogeneous Photonic Integration." in L. Vivien and L. Pavesi, eds. *Handbook of Silicon Photonics*. New York: Taylor and Francis.

¹⁸ C. Doerr (2013). "Highly Integrated Monolithic Photonic Integrated Circuits." *39th European Conference on Optical Communications*, pp. 1-2.

¹⁹ D.J. Lockwood and L. Pavesi (2011). *Silicon Photonics II: Components and Integration*. Berlin: Springer-Verlag.

²⁰ T. Aalto, et. al (2003). "Fabrication and Characterization of Waveguide Structures on SOI." *Proc. SPIE, Integrated Optical Devices: Fabrication and Testing*, Vol. (4944)

²¹ J. Ahmed, et. al. (2014). *Optical Signal Processing by Silicon Photonics*. SpringerBriefs in Materials.

²² I. Artundo, et. al (2013). "Basic Silicon Photonic Building Blocks for Commercial Applications." *Optik&Photonik* 8(2), pp. 53.

Selection of a waveguide structure will be dependent on the advantages offered with respect to a specific application. For example, in a slot waveguide—which consists of two strip waveguides—light is confined in the aperture structure between the two regions of higher index material. This type of geometry is ideal for applications such as biochemical analyte-sensing, where the guided electromagnetic field will be localized in the region of desired overlap with the chemical of interest²³. These and other types of waveguide geometries can be used as fundamental building blocks to construct more complex structures, including splitters, parallel directional couplers, etc²⁴.

- Multimode Interference (MMI) Based Couplers

Multimode interference (MMI) couplers can serve as power splitters and combiners in integrated photonics circuits on different materials platforms and can offer wider fabrication tolerances than those of directional couplers. Modal excitation of multimode waveguides can be achieved through the process of self-imaging, in which a specific input profile can then be subsequently reproduced while traversing through the waveguide²⁵. These reproductions can be formed as single images or multiple images depending on the size of the multimode waveguide. MMI couplers have a discrete number of input singlemode waveguides connected to output singlemode waveguides, with common input-output configurations of 1x2, 1x4, 4x4, etc²².

These input and output waveguides are connected by a wide multimode waveguide, and the distribution input at the multimode waveguide thus excites a series of eigenmodes with different propagation constants. MMI couplers are designed so the interference of the eigenmodes produces a distribution where the power at the input waveguides is then evenly distributed across the output waveguides⁴. MMI Couplers are able to provide routing and coupling across wide bandwidths and are largely polarization sensitive²⁶; this makes them one of the best options as splitting components in integrated photonics devices and a foundational building block for constructing Mach-Zehnder Interferometers.

- Mach Zehnder Interferometers:

Interferometers are the primary building blocks for use in many applications that involve optical systems; specifically, the Mach-Zehnder Interferometer is a common tool for use in applications such as high speed optical modulation and biochemical sensing²⁷. Depending on intended the application, the Mach-Zehnder Interferometer can act as a passive device or as an active device, based on whether or not an electric field is applied to one of the arms for use in electro-optic switching²⁵. The structure of an integrated Mach-Zehnder Interferometer (MZI), as illustrated below, consists of an input waveguide, a Y-junction that divides the input wave evenly across two separate arms, and an output waveguide where the field recombines from the two arms:

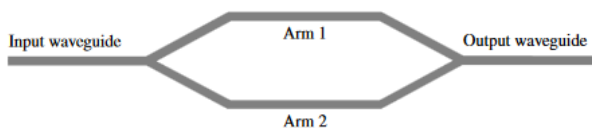


Figure 2.2: General Structure of an Integrated Mach-Zehnder Interferometer²⁷

²³ T. Dar. (2012). "Label-free Slot-waveguide Biosensor for the Detection of DNA Hybridization." *Applied Optics*, 51 (3).

²⁴ S.H. Tao (2011). "Optical Coupling and Splitting with Two Parallel Waveguide Tapers." *Optics Express*, 19 (2).

²⁵ A.K. Dutta, et.al. eds. (2003). *WDM Technologies: Passive Optical Components Volume 1*. San Diego: Elsevier Science.

²⁶ L. Coldren, et. al. (2012). *Diode Lasers and Photonic Integrated Circuits*. Hoboken: John Wiley & Sons, Inc.

²⁷ G.T. Reed and A.P. Knights. (2004). *Silicon Photonics: An Introduction*. Hoboken: John Wiley & Sons, Inc.

When the input field passes through the two arms and recombines at the output waveguide, the two fields may no longer be in phase as a result of variation in optical path lengths of the two arms²². For chemical sensing applications, one of the arms serves as a reference waveguide, and the other as a functionalized sensing waveguide, such that the measured phase difference provides information about the changes in refractive index that occur in the presence of a target-analyte. For use in switching, the relative phase of the two arms can be dynamically altered by using phase modulators to produce modulated intensity outputs.

The outline provided of the above structures gives brief insight into the possible functions achievable using passive integrated photonics structures. Other frequently implemented passive structures include different types of couplers/splitters, arrayed waveguide gratings (AWGs), and microring resonators. Specifically, arrayed waveguide gratings (AWGs) are used to multiplex/de-multiplex input signals of closely aligned wavelengths that enter through the associated input waveguides, functionally acting as an optical prism²⁸. Microring resonators are structured such that an optical waveguide is looped back on itself, and is able to achieve resonance when an optical path length equals an integer number of relevant wavelengths. The possible functions for these types of structures are numerous, extending to use in label-free biosensing and to applications as filters and modulators²⁹. In addition to these passive building block structures for PICs, the library of active building blocks available for use in integrated optics has continued to increase, particularly for InP integrated photonics devices. Available active building block structures presently include distributed feedback (DFB) lasers, distributed Bragg reflectors (DBR) lasers, and semiconductor optical amplifiers (SOAs).

II. Design and Fabrication Ecosystem

a. *Fabrication: Existing Foundry Ecosystems*

For research and technology development efforts, the selection of a specific material platform—such as silicon or indium phosphide—will dictate the available pathways to device fabrication. To achieve precise customization at lower costs, device fabrication at research institutions may be accomplished with institutional/regional manufacturing capabilities. For example, femtosecond laser microfabrication techniques can be used to directly inscribe low-loss waveguide based structures onto transparent dielectric substrates³⁰. Novel silicon integrated photonics device fabrication can be conducted by research groups that have access to facilities for silicon wafer processing, using standard techniques such as plasma-enhanced chemical-vapor deposition (PECVD)³¹. Additionally, larger-scale research and development foundries, including government-funded facilities like the DOE Sandia Laboratories Microsystems Science and Engineering Microsystems Complex and the DoD's Lincoln Laboratory, offer more sophisticated fabrication capabilities for integrated photonics devices.

In comparison to conventional CMOS foundry lines for microelectronics, anticipated volumes for production of integrated photonics products are much lower. These lower production volumes present unique challenges with regards to the high cost barriers for user entry into integrated photonics device development. While specific integrated photonics device manufacturers may maintain robust fabrication facilities, the accessibility to such facilities may be limited because of intellectual property protections. Establishing accessible manufacturing environments that allow for rapid process flows and high yield

²⁸ G. Lifante. (2003). *Integrated Photonics: Fundamentals*. Hoboken: John Wiley & Sons, Inc.

²⁹ W. Bogaerts, et. al. "Silicon Microring Resonators." *Laser Photonics Review*, 6 (1), pp. 47-50.

³⁰ K. Minoshima et. al. (2001). "Photonic Device Fabrication in Glass By Use of Nonlinear Materials Processing with a Femtosecond Laser Oscillator." *Optics Letters*, 26 (19), pp. 1516-1518.

³¹ G. Cocorullo, et. al (1996). "Amorphous Silicon Waveguides and Light Modulators for Integrated Photonics Realized by Low-Temperature Plasma-Enhanced Chemical-Vapor Deposition." *Optics Letter*, 21 (24), pp. 2002-2004.

production are essential for low cost PIC-device development³². This may be accomplished through the use of distinct foundries (fabs), which offer only PIC manufacturing services and are considered “pure-play,” meaning that the foundries themselves do not design and manufacture products. Hybrid models which combine commercial PIC manufacturers’ foundry capabilities for their own products and also accept external business have also been developed. Requirements for the establishment of a fabless design ecosystem include repeatable process flows, consistent design rules and device libraries pertaining to the process flow, and associated computer-aided design, simulation and layout tools³³. The following sections provide a brief overview of integrated photonics foundry services available for research and development purposes and future proposed directions for commercial integrated photonics foundry lines.

i. JePPIX Infrastructure: Indium Phosphide/TriPleX

There exists a robust generic foundry platform in Europe that connects initial user prototypes to selected foundry services through the use of a third-party broker. JePPIX, the Joint European Platform for InP-based Photonic Integrated Components and Circuits, facilitates interaction between all involved parties in the development of PIC devices and acts as this broker between PIC Designers, Design Software Tools, PIC Foundries, and Commercial Packaging Facilities. This generic integration structure is designed to reduce overall entry costs for developing novel PIC products, and facilitates PIC-development paths for both custom runs and for multi-project wafer (MPW) runs. JePPIX coordinates four foundry platforms, provided by the following companies: Oclaro, Fraunhofer HHI, Smart Photonics, and LioniX. Integrated photonics device designers are able to coordinate with JePPIX to complete non-disclosure agreements and access foundry-specific process design kits (PDKs) that provide accurate models and design tools for corresponding software³⁴. If a design does not require extensive customization, it is possible to participate in a multi-project wafer run, such that multiple projects are completed on the same wafer run, which significantly reduces overall cost to the user³⁵. The following pictogram provides a basic overview of process flow found in the current European InP Ecosystem that is coordinated by JePPIX:

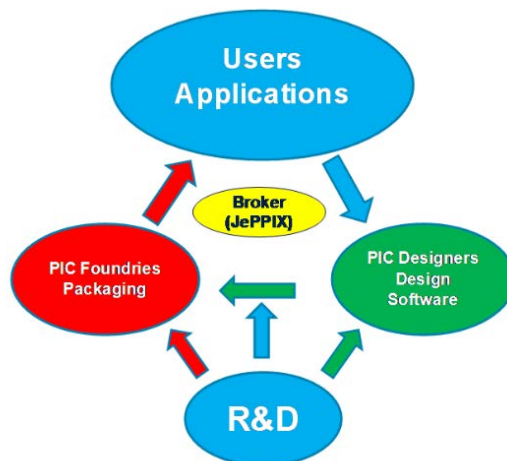


Figure 2.2: Overview of Existing InP/Tripix Fabrication Infrastructure; MPW Scheduled Runs Available:
(<http://www.jeppix.eu/>)

³² M. Hocberg and T. Baehr-Jones. (2010). “Towards Fabless Silicon Photonics.” *Nature Photonics*, 4, pp. 492-494.

³³ A. Eu-Jin Lim et. al (2014). “Review of Silicon Photonics Foundry Efforts.” *IEEE Journal of Selected Topics in Quantum Electronics*. ”

³⁴ JePPIX. (2015). “The Road to a Multi-Billion Euro Market in Integrated Photonics.” *Jeppix RoadMap 2015*. Available: http://www.jeppix.eu/document_store/JePPIXRoadmap2015.pdf

³⁵ M. Smit et.al (2014). “Generic Foundry Model for InP-based Photonics.” *IET Optoelectronics*, 5 (5), pp. 187-194.

If further customization of the fabrication processes is needed for a specific applications, JePPIX is also able to assist with matching desired user specifications with individual foundries for optimal device production. Schedules for design submission, wafer runs, relevant packaging, and device return are all synchronized through the JePPIX broker as well.

Beginning in 2014, JePPIX has worked to coordinate semi-commercial access to MPW runs through three InP foundries—Oclaro, Fraunhofer HHI, and Smart Photonics—and through the LioniX foundry which manufactures devices using a dielectric Si₃N₄/SiO₂ (TriPlex) material platform. Each of these foundries has developed a set of standard, parametrized photonic building blocks, consisting of passive waveguide components, semiconductor optical amplifiers (SOAs), phase modulators, etc. that can be used for the design of complex integrated photonic circuits³⁶. A brief overview of existing foundry capabilities are highlighted in the following table:

| Broker | Process | Lasers | SOAs | TDBR | Modulators / Phase shifters | | | | Detectors | | | Prop loss |
|--------|----------------------|--------|------|------|-----------------------------|---------------------|-----------|---------|-----------|---------|------------------------|-----------|
| | | | | | L (mm) | V _p - Pp | Loss (dB) | B (GHz) | R(A/W) | B (GHz) | I _{dark} (nA) | dB/cm |
| JePPIX | Oclaro TxRx 10G | YES | YES | YES | 1 | 3.5 | < 2 | > 10 | 0.8 | 10 | | 2-3 |
| JePPIX | HHI TxRx 25G | YES | YES | YES | 0.5 | (25 mW) | < 2 | (kHz) | 0.8 | 40 | < 10 | 1-2 |
| JePPIX | SMART TxRx 10G | YES | YES | | 2 | 7 | < 2 | 10 | 0.8 | 10 | < 20 | 3-4 |
| JePPIX | TriPlex (DS-500-170) | | | | 1-2 | (500 mW) | < 0.1 | (kHz) | | | | < 0.5 |

Table 2.1: JePPIX Foundry Overview: Oclaro, Fraunhofer HHI, Smart Photonics, and TriPlex Building Block Parameters³⁷

Each of the foundries provides specific expertise with regards to the photonic building block components, and so selection of an individual foundry may be decided based on several associated factors, including price per run/cost per area (for a MPW run), fabrication process, building block availability, and building block component performance. After a foundry has been selected and an NDA broker agreement has been completed, the foundries provide additional detailed information corresponding to the use of individual building blocks in selected software packages. To date, the use of the JePPIX coordination platform has been successful in establishing a cohesive approach and infrastructure for device production, serving as a model for future integrated photonics fabrication ecosystems.

ii. Existing Foundry Processes for Silicon Photonics and the announcement of the Integrated Photonics Institute for Manufacturing Innovation

Movement towards the establishment of similar fabrication ecosystems to the JePPIX environment for silicon photonics has also been initiated. Previous efforts led by the OpSiS center at the University of Delaware introduced the first fully integrated Silicon photonics ecosystem in the United States. Though the OpSiS project completed in July of 2015, silicon integrated photonics MPW runs are offered through the Europractice Consortium (Imec/LETI/IHP), formerly known as ePIXfab, which tailors specific runs to chips with passive components, full platform technology systems with EO modulators and detectors, and passives with heaters. In 2016, Imec announced that it expanded its process design kit to include building block components able to improve Mach-Zehnder modulators and ring-structure modulators to reach 50

³⁶ K. Lawniczuk (2014). "Photonic ICs in a Generic Foundry." *Conference on Indium Phosphide and Related Materials*, Tu-D3-3.

³⁷ A. Khanna and K. Lawniczuk. (2015). "Foundries Overview." 7 Pennies Consulting. Available: http://www.7pennies.com/downloads/FAB_overview_Amit_Khanna.pdf

Gb/s non-return-to-zero optical lane rates³⁸. This development expands user capability on existing Silicon photonics MPW runs and allows for the realization of higher data rate integrated optical interconnects.

In addition to existing European ecosystems for custom and MPW runs for integrated photonics devices, Vice President Biden recently announced the new American Institute for Manufacturing (AIM) photonics, which will establish integrated photonics fabrication ecosystems within the United States. This Integrated Photonics Institute for Manufacturing Innovation (IP-IMI) will be a New York-based consortium led by SUNY Polytechnic that will bring together government, academic, and industry partners, with announced funding of \$110 million dollars in federal investment and \$500 million dollars in non-federal funds. The IP-IMI has announced 75 associated partners with proposed objective to establish an end-to-end photonics fabrication infrastructure, including integrated design tools, domestic foundry access, and automated packaging techniques³⁹.

b. Current Modeling, Simulation, and Design Techniques

To successfully develop photonic integrated circuits that perform to meet desired specifications and parametric requirements, it is necessary to have the capability to both model device building blocks and to construct CAD designs for foundry fabrication. For most academic and research designers, the engineering design process for integrated photonics circuits will likely follow an iterative path, with similar steps as those detailed in the procedure listed below, in Chart 2.1:

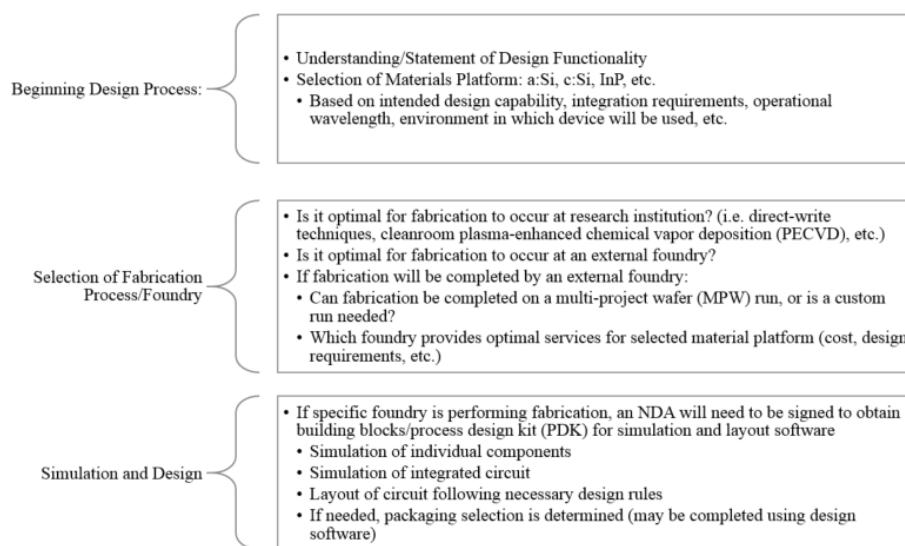


Chart 2.1: Predicted design flow of PIC-development process for research purposes. Experienced PIC designers will likely establish preferred selections for both simulation software and specific foundries/fabrication processes depending on intended device application.

At a fundamental level, application specific PIC designers may want to understand the capabilities of an individual element, such as a waveguide or microring resonator. To fully realize these devices, it is then necessary to interface many individual elements—appropriate to fabrication specification—on a correctly sized chip. There are several existing software packages available to consumers for modeling integrated photonic circuit building block components and predicting device performance. Many of the building block

³⁸ D. Manners (2016). “Imec Enhances 50 Gb/s Silicon Photonics.” *Electronics Weekly*. Available: <http://www.electronicweekly.com/news/research-news/imec-enhances-50gbs-silicon-photonics-2016-03/>

³⁹ National Photonics Initiative (2015). “About the IP-IMI.” Available: <http://www.lightourfuture.org/getattachment/Home/About-NPI/NPI-for-Government/FINAL-NPI-IPIMI-One-Pager-090215-%282%29.pdf>

simulation packages work in conjunction with PIC-design tools that supply process design kit (PDK) libraries appropriate to individual foundry specifications. In this sense, the design elements are linked directly to the capabilities of the foundry. Dependent on the software and foundry selected, additional consultation about design options may be provided by the software design engineers or points of contact from the respective foundries. Software selection for design and modeling tools will be influenced by the designer's selection of material and foundry, as well as whether the PIC being fabricated is a custom run or part of a multi-project wafer (MPW) run. Commercially available tools are routinely presented and are available for demonstration at prominent photonics conferences, such as OFC and Photonics West⁴⁰. Though certainly not an exhaustive list, the most common integrated photonics simulation packages and design suites are detailed below:

Luceda Photonics: IPKISS

IPKISS (<http://www.ipkiss.org/>) is a Python script-based design software, which is described as a “parametric design framework for [photonic] integrated circuits.” The scripted designs are constructed in a modular framework, so that each smaller scale component design can be completed at a detailed individual level and then easily incorporated across circuit designs. Different photonic components can be designed into a parametric cell “PCell,” and then can be used throughout design, to perform simulations, to generate mask layouts, etc. IPKISS represents this fluid process between modular component design and cumulative circuit integration with the following schematic:



Figure 2.2: IPKISS PIC-Design Flow Incorporating the use of PCells⁴¹.

IPKISS was developed in conjunction with Ghent University and the IMEC consortium to produce sophisticated mask design of large silicon PIC-devices. IPKISS also offers a photonic component library, called Picazzo, which can allow for easy copy-paste functionality throughout the modular platform. Specifically, the Picazzo script library includes developed tools for the insertion of photonic building block components, such as splitters, ring resonators, Mach-Zehnder Modulators, etc.—which can be customized as needed for user design in the associated scripting environment. Example scripts for these and similar components are accessible on the IPKISS website for brief demonstration. There are additional plug-ins available for specific PIC-designs, including structuring input/output ports, and for advanced visualization techniques. The Pysimul tool available in IPKISS provides interface with the developed PIC designs to external simulation tools, such as mode-solvers or circuit simulators. The Python script-based environment requires that designers have a level of competency in Python coding; however, the script environment also allows a significant amount of flexibility and design-freedom for the user. IPKISS offers the following PDKs: IMEC Passives, imec iSiPP25G, IHP, IME⁴². Though the primary building blocks available are

⁴⁰ OFC. (2016). “PIC Workshop: All You Need to Know in Order to Make a Photonic IC.” Available: <http://www.7pennies.com/news-events/pic-ofc-2016/>

⁴¹ IPKISS. “Technical Overview.” *Luceda Photonics*. Available: <http://www.ipkiss.org/technical-overview/photronics-examples>

⁴² Luceda Photonics. (2016). “The IPKISS Design Framework.” Available: <http://www.lucedaphotonics.com/en>

tailored to the design of silicon integrated photonics, the modular design format can allow for customization to different material platforms⁴³.

Lumerical:

Lumerical Solutions Inc. (<https://www.lumerical.com/>) offers a full-design suite with different software tools applicable to address various design challenges and simulation requirements for photonic component and circuit design. Different pieces of Lumerical software relevant to PIC-design are specifically tailored to optical component simulation and device simulation, and tools for electrical and thermal simulation are also offered. The FDTD Solutions software available through Lumerical is a three-dimensional finite-difference time-domain (FDTD) Maxwell solver that can be used for optimization of photonic devices. The MODE Solutions package has the ability to build 1D, 2D, and 3D models for waveguide and basic-PIC component structures, and provides modal analysis, an Eigenmode Expansion solver, and a 2.5D analysis tool for FDTD propagation. Lumerical's INTERCONNECT software tool is the most sophisticated PIC design and analysis tool that it offers, with a range of tools and solutions for optimizing design functionality. INTERCONNECT provides a schematic editor that also can use a script/MATLAB interface, which allows the designer to view the hierarchical structure of the designs. The INTERCONNECT tool includes a circuit solver, the ability to import structure from FDTD Solutions/MODE Solutions, and a library of pre-structured PIC elements.

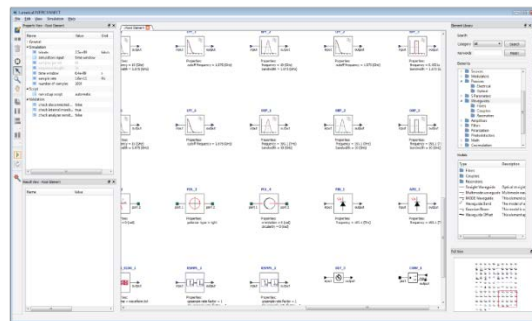


Figure 2.3: Screenshot of INTERCONNECT PIC Element Library⁴⁴

The Lumerical INTERCONNECT software can be operated with other photonic software design packages, providing integration with Cadence Virtuoso software, Mentor Graphics, and Phoenix Optodesigner⁴⁵. This integration provides greater flexibility for using Lumerical across foundries and materials platforms. Lumerical has also partnered with Sandia National Laboratories to develop precise compact model libraries specific to Sandia's fabrication and manufacturing process⁴⁶. Trial versions of Lumerical Solutions are accessible via their website for evaluation of software tool performance⁴⁷.

⁴³ J. Hofrichter. (2012). "InP Microdisks for Optical Signal Processing and Data Transmission." *Eindhoven University of Technology Library*. Available: <https://pure.tue.nl/ws/files/3603335/750668.pdf>

⁴⁴ Lumerical. "INTERCONNECT: Photonic Integrated Circuit Design and Analysis Environment." Available: <https://www.lumerical.com/tcad-products/interconnect/>

⁴⁵ Cadence. "Photonics Solution: Integrated Electronic/Photonic Design Automation Environment." Available: <http://www.cadence.com/solutions/photonics/Pages/default.aspx>

⁴⁶ (2014). "Lumerical Solutions and Sandia Laboratories Collaborate to Advance Photonic Integrated Circuit Design and Manufacture." *Photonics Online*. Available: <http://www.photonicsonline.com/doc/lumerical-solutions-and-sandia-national-laboratories-collaborate-0001>

⁴⁷ Lumerical Solutions Products. (2016). "30-Day Evaluation." Available: <https://www.lumerical.com/downloads/>

Phoenix Software: Optodesigner:

Phoenix software offers a comprehensive set of integrated optics and photonic chip design solutions through their OptoDesigner environment. Phoenix Software provides a cohesive suite of software tools, consisting of several features for photonics mode simulations, photonic propagation simulations visualization of process flow, and chip and mask layout. The chip and mask layout tools let the user control design of chip layout and manage functional relationships between corresponding components. These tools contain standard libraries of photonic elements/building blocks, and have capability to interface with external foundry PDK/design rule sets for Silicon, InP, and other material platforms. The Photonic mode simulations tool integrates mode solutions, and thermo-optic, electro-optic, and stress-optic simulations, using full vectorial film mode matching and finite difference technologies. The photonic propagation simulations package provides simulation of light propagation in PIC devices and offers several propagation techniques. All of these tools are available independently, or as a set within the OptoDesigner environment⁴⁸. Additionally, the Application Specific Photonic Integrated Circuit (ASPIC) tool, which is an advanced simulator for analysis of optical circuits—and can be integrated with either MatLAB or Python scripts—is accessible through the OptoDesigner environment. The OptoDesigner software package facilitates the steps of PIC-design from component simulation and layout through the final stages of design, including layout verification and packaging.

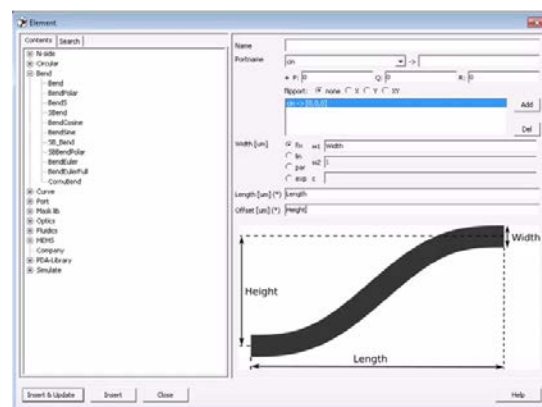


Figure 2.4: Example of Sine-Bend Building Block from Element Library Using Phoenix Optodesigner

Additional presentation of the Optodesigner building blocks and software tools and display of the interface between Lumerical INTERCONNECT and Phoenix Optodesigner 5 tools are available through Phoenix software's online video demonstrations⁴⁹.

PhotonDesign: PICWAVE, FIMMPROP

PhotonDesign is a photonic design software company specializing in the development of innovative photonics CAD tools for both active and passive components. Specifically tailored for simulation and design of photonic integrated circuits, PhotonDesign offers the FIMMPROP and PICWAVE software tools. FIMMPROP can be used for modeling optical propagation in PIC-waveguide structures, using a rigorous Eigenmode Expansion (EME) method. This tool allows designers to simulate and optimize standard building block elements such as MMI couplers and ring resonators, and can also be used for modeling of optical gratings. Beyond the standard building blocks, FIMMPROP also provides unique modeling tools

⁴⁸ Phoenix Software (2015). "OptoDesigner 5: Photonic Chip Design Solutions." Video, Available: <https://www.youtube.com/watch?v=tyFBIVA8o4Q>

⁴⁹ Phoenix Software Channel, Videos. Available: https://www.youtube.com/channel/UCu3I-FghiHlb0TOdrLzvcYg/videos?sort=dd&shelf_id=0&view=0

for plasmonic waveguides and photonic crystal fiber devices. Once components have been modeled with the FIMMPROP tool, they can be exported to the PICWave tool, where they can be combined and simulated as fully integrated circuits.

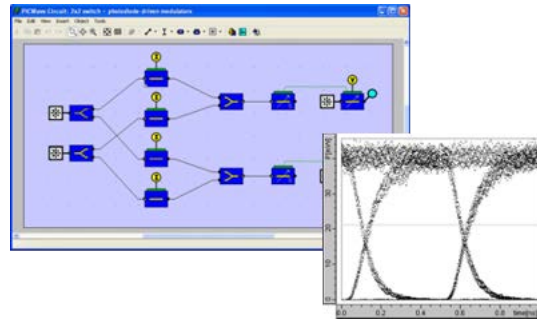


Figure 2.5: Photon Design Photonic Circuit Simulator and associated eye diagram⁵⁰

PICWave functions as a photonic circuit simulator to model the interaction of multiple photonic components on a larger circuit. It is a uniquely sophisticated simulation tool in that it incorporates a time-domain model to combine both active and passive circuit elements. Similarly to design flow tools offered by other photonic design software companies, PICWave provides the user with the ability to create their own building block library or to import design kit libraries to design PICs with foundry-specific components. Thirty-day evaluation versions of FIMMPROP and PICWave may be requested via the Photon Design website⁵¹. In addition to consulting services offered by foundry representatives and engineers affiliated with integrated photonics modeling software companies, external photonics design houses have been established to provide engineering solutions to individual customers. Companies such as VLC Photonics⁵² provide assessment of device proposal, evaluate feasibility of device integration, assist with cost estimation, and guide users in best practices for design, layout, fabrication, packaging, and testing.

c. Sophisticated Commercial Technologies

The design processes and foundry ecosystems described in sections a. and b. above are most pertinent for applications in research and development of photonic integrated circuits. This infrastructure is of central importance for ongoing academic and government-sponsored research, and will continue to inform future pathways for innovation in PIC-design. At this time, the commercial development of integrated photonic technologies is still in nascent stages and much of the work completed by industrial manufacturers has been for the purposes of technology demonstration, instead of mass production and implementation. In the commercial space, some of the existing foundries also operate as commercial manufacturers. Well-known electronics manufacturers have also expanded to include manufacturing of integrated PICs, while comparatively new photonics companies have been developed with specific emphasis on the development of integrated optics devices. As commercial PIC development is perhaps closer-to-market than many areas of research investigation, it is likely that these commercial efforts would be of use in the near-future for implementation in space systems applications. Recent forecasts expect that the commercial photonic integrated circuits market will continue rapid growth over the period of 2016-2022, at which time it will reach a predicted market value of \$1.3billion⁵³. A brief overview of highlighted industrial leaders amongst

⁵⁰ Photon Design. (2010) "PICWave: A Photonic IC Circuit and Laser Diode/SOA Simulator." PDF Available: https://www.photond.com/files/brochures/PicWave_brochure.pdf

⁵¹ Photon Design. (2016). Evaluation Website, Available: <https://www.photond.com/evaluation.htm>

⁵² I. Artundo. (2016). "Photonic Circuit Design, Coming of Age in a Fabless Ecosystem." *EE Times, Europe*. Available: <http://www.electronics-eetimes.com/news/photonic-circuit-design-coming-age-fabless-ecosystem>

⁵³ Credence Research (2016). "Photonic Integrated Circuits Market to Reach US \$1.31 Bn by 2022." *Energy and Power*. Available: <http://www.credenceresearch.com/report/photonic-integrated-circuits-market>

domestic markets—and respective associated specialties in integrated photonics—is provided in the table below.

| Company: | Specialization: | Recent Developments: |
|---|--|--|
| 1. Infinera Corporation (2000): Sunnyvale, CA (https://www.infinera.com/company/about-infinera/) | Manufacturer of wavelength division multiplexing equipment for telecommunications, pioneer in design of integrated photonic circuits. In 2004, produced first large-scale integrated photonics chip, a 10-channel transmitter, where each channel operated at 10 Gb/s. Infinera does not produce photonic integrated circuits as individual commercial products, but instead integrates them to optical data transmission systems. | Infinera has developed PIC-Module transmitters and receivers with 500 Gb/s capabilities. ⁵⁴ For a variety of milestone demonstrations, Infinera has continued to develop transmitter and receiver PICs, and has worked to produce the world's first PIC-based terabit coherent superchannel trial ⁵⁵ . |
| 2. IBM (1911): Armonk, NY: (http://www.zurich.ibm.com/st/photonics/silicon.html) | Multinational computing and technology corporation traditionally known for manufacturing and marketing computer hardware, software, and associated infrastructure. IBM also operates twelve research laboratories worldwide, which includes research groups specializing in Silicon photonics and Optical Interconnects. | IBM has demonstrated fully integrated wavelength multiplexed silicon photonics chips. To date, IBM has not announced timelines for use of such circuits in commercial products, but it is predicted that such optical component technologies may be used for server-to-server linkages ⁵⁶ . |
| 3. Intel Corporation (1968): Santa Clara, CA (http://www.intel.com/content/www/us/en/research/intel-labs-silicon-photonics-research.html) | Like IBM, Intel is an American multinational company known primarily for manufacturing computer hardware as one of the world's largest and highest values semiconductor chip maker. Intel also maintains a research approach to PIC development with the Intel Silicon Photonics Simulation group. | In 2013, Intel And Corning announced an optical Connector technology (MXC), for which production would begin in 2014. Intel has also announced that it will build the world's first Optical PCI Express server, and has demonstrated integrated photonics technology modules operating at 100Gb/s ^{16, 57} . |
| 4. Acacia Communications (2009): Maynard, MA (http://acacia-inc.com/acacia-advantage/silicon-photonics-integration/) | Acacia Communications is a manufacturer of high-speed coherent optical interconnect products intended to improve performance and capacity of communications networks. Existing produces include low-power silicon PICs integrated into different optical interconnect modules over a range of transmission speeds for use in both long-haul and data center applications. | Acacia Communications produces has developed PIC-technologies consisting of monolithic coherent silicon-based transceivers with integrated laser and gain elements, with functional wavelengths from 1260 to 1630 nm ⁵⁸ . Acacia Communications announced filing to launch an IPO at the end of 2015, indicating recent developments in market growth for optical subsystems. |
| 5. NeoPhotonics Corporation (2002): San Jose, CA (https://www.neophotonics.com/product/) | NeoPhotonics Corporation is a well-known manufacturer of hybrid PIC-modules for high-speed communications networks, and develops photonic elements in-house using Silicon, Indium Phosphide, and Gallium Arsenide wafer fabrication. | NeoPhotonics constructs photonic integrated circuits from different materials that are subsequently combined for their hybrid integration technology, producing products such as the Integrated Coherent Receiver (100G Coherent Transport). An array of PIC-based products including optical switches, |

⁵⁴ F. Kish (2014). "500 Gb/s and Beyond PIC-Module." *Optical Fiber Communication Conference*, paper W31.1

⁵⁵ Infinera. (2015). "Coherent DWDM Technologies." White Paper, Available: https://www.infinera.com/wp-content/uploads/2015/07/Infinera_Coherent_Tech.pdf

⁵⁶ S. Anthony. (2015). "IBM Demos First Fully Integrated Monolithic Silicon Photonics Chip." *Ars Technica*. Available: <http://arstechnica.com/information-technology/2015/05/ibm-demos-first-fully-integrated-monolithic-silicon-photonics-chip/>

⁵⁷ A. Alduino. (2016) "Demonstration of a High Speed 4-Channel Integrated Silicon Photonics WDM Link with Hybrid Silicon Lasers." Available: http://www.hotchips.org/wp-content/uploads/hc_archives/hc22/HC22.23.330-1-Alduino-Intel-SiP-Link.pdf

⁵⁸ C. Doerr et. al. (2016). "O,E,S,C, and L Band Silicon Photonics Coherent Modulator/Receiver." *Optical Fiber Communications Conference*, paper Th5C.4. Available: <https://www.osapublishing.org/abstract.cfm?uri=OFC-2016-Th5C.4>

| | | |
|---|---|---|
| | | passive components, and high-speed ICs are also offered. |
| 6. Freedom Photonics: Santa Barbara, CA (http://freedomphotonics.com/) | Freedom Photonics develops high-performance, reliable integrated photonic components for application to optical communications, optical sensors, and medical equipment. Their PIC technologies are built on compound semiconductor platforms, Silicon-Germanium CMOS, and planar lightwave waveguide platforms. Freedom Photonics has developed out of the high-tech photonics research ecosystem connected through the UC Santa Barbara College of Engineering ⁵⁹ . | Commercially, Freedom Photonics offers monolithic InP based tunable laser chips with center wavelengths at 1300 nm and 1550 nm, and also offers an InP C-Band tunable transmitter with a 45 nm tuning range. Freedom Photonics has been awarded a NASA Tipping Point Grant for the development of Low Size, Weight and Power (SWaP) Instruments for Remote Sensing Applications ⁶⁰ . |

Many of the companies detailed above are current market leaders; however, investment in research and development of commercial integrated photonics products is experiencing a period of rapid growth. As previously mentioned, the Integrated Photonics Manufacturing Innovation Hub announced 75 key partners to develop a PIC-manufacturing ecosystem in the United States. Of the 75 key partners, 55 are commercial photonics companies in the United States⁶¹. Currently, it is estimated that the top four companies currently account for approximately forty-five percent of global revenue in integrated photonics, with the largest share of this revenue concentrated in optical communications. High-manufacturing costs still serve as a significant barrier to product development at a large scale and present challenges for overall system-level integration with sufficient reliability, but it is anticipated that the development of the IP-IMI will allow for greater product innovation and directed industry implementation⁶².

III. Potential Space System Applications for Integrated Photonics

There exist many areas of overlap regarding the benefits of integrated photonics devices for both terrestrial and space applications; however, the improvements offered by the scalability of size, weight, and power for integrated photonics are of significant value when considering the cost per pound to fly instruments on space missions. Most recently, NASA's Space Technology and Mission Directorate (STMD) has awarded Early Stage Innovation awards to university-led teams for research involving integrated photonics devices in optical communications. In addition to these awards, the NASA Goddard Space Flight Center has announced plans for the development of the first integrated photonics modem, with an anticipated test date in 2020 on the International Space Station. While many of the clearest pathways for space based devices using PICs involve the development of technologies for communications systems, the scope of impact of integrated photonics extends to an array of fields, including sensing, biological applications, navigation, and imaging. In addition to the following proposed application areas for space-systems technologies, a Department of Defense has released a Technical Assessment of Integrated Photonics with further relevant areas of investigation⁶³.

⁵⁹ S. Fernandez (2015). "UC Santa Barbara is West Coast Hub for Photonics Institute." *UC Santa Barbara, News*.

⁶⁰ NASA (2015). "NASA Announces New Public-Private Partnerships to Advance "Tipping Point," Emerging Space Capabilities." Available: <http://www.nasa.gov/spacetechnology>

⁶¹ The White House Office of the Vice President. "Vice President Biden Announces New Integrated Photonics Manufacturing Innovation Hub in Rochester, NY."

⁶² V. Coffey. (2014). "Photonic IC Market to See Remarkable Growth Through 2019." *The Optical Society: IndustryNews*. Available: [http://www.osa-](http://www.osa-opn.org/home/industry/2014/april/photonic_ic_market_to_see_remarkable_growth_throug/?feed=Industry)

[opn.org/home/industry/2014/april/photonic_ic_market_to_see_remarkable_growth_throug/?feed=Industry](http://www.osa-opn.org/home/industry/2014/april/photonic_ic_market_to_see_remarkable_growth_throug/?feed=Industry)

⁶³ Department of Defense Research and Engineering. (2015). Technical Assessment: Integrated Photonics. Available: http://www.defenseinnovationmarketplace.mil/resources/OTI_Integrated_Photonics_Tech_Assessment_vPublic.pdf

a. Sensing

NASA missions involve instrumentation for both remote sensing and direct sensing applications. Remote sensing includes such techniques as laser altimetry, LIDAR sensing, laser ranging, and spectrometry to perform observations about material objects from a distance, without coming into direct contact with the object of interest⁶⁴. Conversely, direct-sensing requires immediate contact with targeted material or object of interest in order to register and collect the appropriate information. Direct sensors are typically based off of laboratory instruments and are designed for use in environments where a directed signal/stimulus—e.g. an electrical signal or the presence of a chemical—can then generate relevant data in a readable output⁶⁵.

At this time, integrated photonics have only been incorporated in a very limited capacity for instrumentation built for remote sensing purposes. Though specific device parameters for PICs depend on base material, device structure, and light source, the output power limitations at the scale of most integrated photonics devices may not be ideal remote sensing applications. However, it is certainly conceivable that integrated photonics devices could be substituted in place of conventional bulk optics systems for remote sensing, provided that appropriate signal amplification can be achieved. Possible avenues for integration include systems such as the pulsed LIDAR sensing instrumentation used in the NASA ASCENDS mission for measurement of atmospheric CO₂ concentrations. The current space LIDAR instrument developed for this mission uses a tunable diode seed laser in a master-slave configuration locked at the wavelength of interest, which is then amplified using several stages of fiber power amplifiers⁶⁶. The laser architecture used for this mission could be functionally developed at a smaller size and power scale on an InP integrated photonics chip with the required frequency-locking⁶⁷. While there have not been extensive investigations into the use of integrated photonics for remote sensing, future applications remain an active area of interest for both U.S. and European government and industry-based research⁶⁸.

Examining the development of direct-sensing technologies, examples of instruments designed for previous and current NASA missions include the following: dust detectors on the Galileo spacecraft which measured mass, charge, and quantity of dust particles; spectrometers on the Cassini spacecraft which can identify chemical species that form the composition of a planetary surface⁶⁹; and radiation assessment detectors on the Mars Rover Curiosity, which assist in characterization of the radiation environment⁷⁰. The development of integrated photonics devices for direct sensing systems similar to these examples is at a more advanced stage than that of remote sensing, and there exist clear paths for translation from larger sensing instrumentation to PIC structures with improved SWaP-C characteristics.

One of the most common forms of integrated photonics direct-sensing structures involves surface sensing on waveguide-based devices, in which sensing of a chemical species is typically performed by measuring a change in the property of a waveguide refractive index. Chemical/analyte sensing can be performed using such structures as ring resonators and Mach-Zehnder interferometers with high

⁶⁴ NASA Earthdata. (2016). “Remote Sensors.” Available: <https://earthdata.nasa.gov/user-resources/remote-sensors>

⁶⁵ J. Fraden. *Handbook of Modern Sensors: Physics, Designs, and Applications*. Switzerland: Springer International Publishing, 2016.

⁶⁶ Yu, A. et al. (2015). “Fiber-Based Laser Transmitter at 1.57 μm for Remote Sensing of Atmospheric Carbon Dioxide from Satellites.” Available: <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150021205.pdf>

⁶⁷ Alt, S. (2015). “Optical Communications Technology: Photonic Integrated Circuits and Fiber Amplifiers.” Summer Internship Presentation: NASA Goddard Space Flight Center.

⁶⁸ D. Macovei. (2015). “Why the next phase of integrated photonics is important for startups.” *Photonic Integration Conference*.

⁶⁹ NASA Jet Propulsion Laboratory. “Chapter 12: Typical Science Instruments.” *Basics of Space Flight*. Available: <https://solarsystem.nasa.gov/basics/bsf12-1.php>

⁷⁰ NASA Mars Science Laboratory. “Sensor on Mars Rover to Measure Radiation Environment.” Available: http://www.nasa.gov/mission_pages/msl/news/msl20101109.html

sensitivities and low limits of detection, on the order of 10^{-7} /RIU⁷¹. The chemical or analyte of interest can be sensed by passing through a functionalized surface, which then induces a refractive index change in the waveguide device so that the signal can then be processed and recorded⁷². These waveguide-structured sensing devices have been developed for numerous liquid-chemical sensing applications, and this functionality has been extended to demonstrate on-chip mid-IR spectroscopic analysis of organic cyclohexane based-solutions⁷³. Additionally, gas detection has been achieved in silicon integrated photonics devices by using a high confinement resonant cavity made with slotted waveguides. With this structure, it is also possible able to measure effective index changes as a function of changes in index of refraction of the surrounding gas^{74,75}. These sensing techniques would be applicable to any future NASA missions and instrumentation involving sensing, including use on applications similar to surface chemical identification on the Mars Rover labs-on a chip or for direct atmospheric chemical analysis.

In addition to the gas and liquid chemical sensing techniques possible with PIC-devices, integrated photonics also holds promise for use in application to radiation detection. Numerous radiation measurement devices and experiments have been flown on missions on the International Space Station and on the Mars Rover labs to better characterize the makeup of the radiation environment around Earth and in deep-space. Improved understanding of these environments allows both for enhanced radiation protection of humans on space missions and shielding of electronic instrumentation. Recently, scintillator materials used for radiation detection have been interfaced with integrated nanophotonics, with results that demonstrated an increased light extraction efficiency⁷⁶. The scale of photonic crystals or microcavities used with the scintillator materials and the improvements in efficiency suggest that integrated photonics technologies could be used for lightweight radiation detection instrumentation in space.

b. Biological Applications

Biological sensing is also relevant to ongoing NASA missions that seek to better understand and address health concerns for astronauts during space flight. Additionally, improved sensing capabilities may be of use for continuing investigations in the fields of astrobiology and space biology⁷⁷. As with the aforementioned applications in chemical sensing, the general nature of biological sensing requires the ability to identify the presence and quantity of a specific biomarker of interest, which may be accomplished by targeted binding between specific analyte-antibody structures. In the waveguide based structures of PIC devices, the device sensitivity is determined by the overlap of the evanescent field with the analyte of interest. The geometric structure, quality factor, and polarization of light can be adjusted with the intention of obtaining the smallest limits of detection. Sensing methods can implement bulk sensing, which looks at the variation of analyte concentration, or by surface sensing, which results from the binding of molecules to a surface on the waveguide functionalized with selectively immobilized markers. Transverse electric (TE) and Transverse magnetic (TM) mode profiles produce different field distributions in the sensing region

⁷¹ K. Worhoff, R. Heideman, A. Leinse, and M. Hoekman. (2015). "Triplex: A Versatile Dielectric Photonic Platform." *Advanced Optical Technologies*. 4(2).

⁷² V. Passaro et al. (2012). "Recent Advances in Integrated Photonics Sensors." *Sensors* 12m 15558-15598.

⁷³ Y. Chen, H. Lin, J. Hu, and M. Li (2014). "Heterogeneously Integrated Silicon Photonics for the Mid-Infrared and Spectroscopic Sensing." *ACS Nano*, 8(7).

⁷⁴ J. Robinson, L. Chen, and M. Lipson. (2008). "On-Chip Gas Detection in Silicon Optical Microcavities." *Optics Express*. 16(6) 429-4301.

⁷⁵ Z. Han et al. (2016). "On-Chip Mid-Infrared Gas Detection Using Chalcogenide Glass Waveguide." *Appl. Physics Letters*. 108, 141106.

⁷⁶ Y.S. Yi and B. Liu. (2015). "Scintillator Detectors with Integrated Nanophotonics for Medical Imaging." *Photonics Spectra*.

⁷⁷ NASA Biological Research. (2015). "Space Station Bio Includes a Bonanza of Biological Research." Available: https://www.nasa.gov/mission_pages/station/research/news/biological_research

and the surrounding materials, and so can be selected for sensing purposes based upon the sensitivity required and the distance the molecule of interest extends from the waveguide surface⁷⁸.

The ability to monitor metrics related to astronaut health and physiology is of value in order to understand the impact of increasing lengths of time in space on the human body. This is particularly important when considering the potential for future deep-space travel. In-flight biological sensors for astronaut health monitoring must be designed to meet many specific requirements for implementation. Among these requirements, devices must provide reliable, rapid information feedback and must be as minimally invasive as possible⁷⁹. Integrated photonics biosensors are able to meet these requirements, and offer further advantages because minimal analyte sample volume is required for use.

Additionally, many PIC biosensors have been developed with reusable cartridges. For example, an interferometric silicon-based photonic device was designed to incorporate a disposable microfluidics platform; this device demonstrated refractive index resolution corresponding to a protein mass coverage resolution of 20 fg/mm²⁸⁰. Integrated photonics biosensing devices have been constructed for a range of applications, such as the detection of salmonella in blood samples. For in-flight use, appropriate monitoring for astronaut health might include blood or salivary samples to measure metabolic information or biometric data related to oxygen and pH levels. Parameters including reusability, increased limits of detection, size/portability, and ease of integration are all advantages of integrated photonics for the purpose of in-flight biological/health-monitoring. Continuing work, such as the development of flexible integrated photonics offer further possibilities for potential wearable health-monitoring systems⁸¹.

The Photonic Biosensor for Space Applications (PBSA) project has been specifically developed to address the challenges biomonitoring of humans in the space station and to take relevant measurements for astrobiology experiments⁸². The PBSA instrument combines a lab-on-a-chip device structure and a photonic immunosensor for use in microbial monitoring. Specifically, the PIC structure for the PBSA-device involves silicon nitride rings and waveguide printed onto silicon, with the microring surface functionalized for specific target antibodies. This device can perform near-simultaneous measurement of at least six target substances using the associated fluidic channels. Applications specifically proposed for this device include the monitoring of microbial contamination on space stations or future planetary habitats⁸³.

c. Communications

The development of superior optical communications systems is one of the clearest applications for the use of integrated photonics devices. Photonic integrated circuits offer the ability to incorporate multiple optical functionalities on a single chip, and are able to allow for increased bandwidth and transmission capabilities. Applications of integrated photonics may include chip-to-chip interconnects and optical transceivers for use in high volume data centers⁸⁴. Compared to electronic counterparts for applications in communications, integrated photonics affords larger bandwidth, lower loss, requires less power, and do not require electro-optic conversion. Over the previous five years, U.S. corporations and industry-partners have considerably advanced the commercially available integrated optics-transceiver technologies. Acacia

⁷⁸AB Gonzalez-Guerrero Et al (2011). "Advanced photonic biosensors for point-of-care diagnostics". *Procedia Engineering*, 25 (1), 71 -75.

⁷⁹ E. Sharifahmadian, Y. Choi, and S. Latifi. (2014). "New Sensors could evaluate astronauts' vital signs in flight." Available: <http://spie.org/newsroom/technical-articles/5321-new-sensors-could-evaluate-astronauts-vital-signs-in-flight>

⁸⁰ K. Zinoviev and A. Gonzalez-Guerrero. al (2011). "Integrated Bimodal Waveguide for Interferometric Biosensor for Label-Free Analysis." *Journal of Lightwave Technology*.

⁸¹ J. Hu et al. (2013). "Flexible integrated photonics: Where materials, mechanics, and optics meet." *Optics Materials Express*, 3 (9): 1313-1331.

⁸² G. De Diego-Castilla, et. al (2015). "A Photonic Biosensor for Space Applications." *46th Lunar and Planetary Science Conference*. Available: <http://www.hou.usra.edu/meetings/lpsc2015/pdf/2109.pdf>

⁸³ S. Pantoja, et. al. (2015). "Nanophotonic Biosensor for Space Exploration." *International Conference on Space Optics*.

⁸⁴ S. Meister et.al (2012). "Photonic Integrated Circuits for Optical Communications." *Optoelectronics*, 7 (2).

Communications has developed a 400-Gbps coherent transceiver module⁸⁵, and Infinera Corporation offers 500Gbps super-channel bandwidth for data center interconnects through its Cloud Xpress product line, in addition to its work on long-haul communications involving integrated photonics⁸⁶.

The possibilities for use of commercially available integrated photonics devices is relevant for use in NASA communications systems, and is an area of active research and development. The NASA STMD Early Stage Innovation Awards recently selected five university-led teams to lead areas of investigation including platforms for terabit-scale communications, modulators for high-efficiency transmitters, and space-based optical communications/ranging⁸⁷. NASA has also recently announced the development of the agency's first integrated photonics modem that will be tested on the ISS in 2020 as a part of the Laser Communications Relay Demonstration (LCRD). The modem, known as the LCRD LEO User Modem and Amplifier (ILLUMA) will act as a LEO terminal for LCRD, and aims to reduce size and power consumption of previous bulk optics while improving performance and reliability⁸⁸.

d. Autonomous Navigation/Positioning

Integrated photonics devices also offer potential for use in autonomous navigation and positioning systems. Ring-resonator structured sensing devices have been used for the development of integrated photonics-based optical gyroscopes. These devices are able to sense and determine angular velocity of inertial systems, which has significant applications for positioning¹⁰. Presently, both fiber optic gyroscopes and active gyroscopes are used in commercially available satellite navigation systems; however, the ability to use small scaled integrated photonics devices for the same purposes would allow for similar navigation systems on CubeSats. The integrated structure can also increase device reliability and potentially lower overall systems costs for positioning and attitude determination of space systems.

Integrated photonics-based optical gyroscopes—also known as integrated optical gyros (IOGs)—operate by taking advantage of the Sagnac Effect, such that the occurring rotation causes measurable phase shifts as a function of the angular velocity⁸⁹. At this time, several IOG device prototypes have been proposed, fabricated, and analyzed using different material platforms and design structures. These designs highlight advantages of IOG function for use in space environments, including the removal of mechanical parts, minimal required maintenance, and insusceptibility to damage or failure induced by vibrations during launch⁹⁰. Four of these device structures are highlighted in the following table, comparing materials system used and the associated figures of merit assessing the IOG performance:

| IOG Device/Material: | Highlighted Design Elements | Resolution: | Bias Drift |
|--|--|---|--|
| 1. High-Q InP IOG (2016) ⁹¹ | Sensing element: ring resonator coupled to a straight bus waveguide through an MMI coupler; operating wavelength = 1.55 μm ; fully integrated InP structure using COBRA processes | <ul style="list-style-type: none"> Use of spiral cavity sensor (Q-factor = 590,000) produced resolution $\sim 150^\circ/\text{h}$ | With spiral resonator, bias drift can be decreased down to $\sim 1^\circ/\text{h}$ |

⁸⁵ S. Hardy (2015). "Acacia Communications offers 400-Gbps Coherent Transceiver Module." *Light Wave Online*. Available: <http://www.lightwaveonline.com/articles/2015/03/acacia-communications-offers-400-gbps-coherent-transceiver-module.html>

⁸⁶ LightWave. "SEACOM demos 100-Gbps via Infinera 500-Gbps PIC." *Light Wave Online*. Available: <http://www.lightwaveonline.com/articles/2011/08/seacom-demos-100-gbps-via-infinera-500-gbps-pic-126522618.html>

⁸⁷ NASA. (2016). "NASA Selects Five Integrated Photonics Research Projects." Available: <http://www.nasa.gov/feature/goddard/2016/nasa-selects-five-integrated-photonics-research-projects>

⁸⁸ NASA (2015). "NASA Engineers Tapped to Build First Integrated-Photonics Modem." Available: <http://www.nasa.gov/feature/goddard/2016/nasa-engineers-tapped-to-build-first-integrated-photonics-modem>.

⁸⁹ A.K. Gupta. (2009). "Photonics Technologies for Advanced Electro-Optic Sensors." *DRDO Science Spectrum*, 102 – 113.

⁹⁰ S. Srinivasan et al. (2014). "Design of Integrated Hybrid Silicon Waveguide Optical Gyroscopes." *Optics Express*, 22 (21)

⁹¹ C. Ciminelle et. al (2016). "A High-Q InP Resonant Angular Velocity Sensor for A Monolithically Integrated Optical Gyroscopes." *IEEE Photonics Journal*, 8 (1).

| | | | |
|--|---|--|---|
| | | <ul style="list-style-type: none"> Up-scaling device with spiral resonator, resolution = $10^\circ/\text{h}$ | |
| 2. Hybrid Silicon Waveguide Optical Gyroscope (2014) ²⁸ | Fully integrated, low-loss silicon nitride spiral waveguide structure. | <ul style="list-style-type: none"> Minimum value = $19^\circ/\text{h}$ | Not specified; Loss reported at 1 dB/m |
| 3. IOG using Long-Range Surface Plasmon-Polariton Waveguide Resonator (2013) ⁹² | Use of a Long-Range Surface Plasmon-Polariton (LRSPP) waveguide structure to overcome propagation loss/polarization extinction ratio challenges associated with conventional waveguides; LRSPP ring resonator = sensing element, consisting of a Si substrate, silver strip and Erbium-doped phosphate glass. | <ul style="list-style-type: none"> Sensitivities = $10^{-3}^\circ/\text{hr}$ (waveguide with single-turn resonator); $10^{-4}^\circ/\text{hr}$ (waveguides with multi-turn resonator) | Reported maximum zero drift 4 orders of magnitude lower than conventional single-mode waveguides. |
| 4. SiO ₂ Waveguide Resonator used in IOG ⁹³ | Si-based ring resonator model, made up of track-pattern ring channel waveguides. Ring resonator design fabricated using PECVD method. | <ul style="list-style-type: none"> Rate detection limit of limit of $1.7^\circ/\text{hr}$ reported | Not specified; Propagation loss of 0.02 dB/cm reported |

The reported quantities for measuring IOG performance indicate progressive improvements towards the development of commercially viable integrated photonics positioning systems with good resolution and minimal drift. For high-performance use in space-systems and in satellites, continued progress towards advancing resolution/drift qualifications are needed to meet application requirements of $0.01^\circ/\text{hr}$ and $1^\circ/\text{hr}$, respectively⁹⁴.

e. Imaging (Astronomy)

Another area of interest for integrated photonics in space applications is the development of astronomical imaging instrumentation (“astrophotonics”). The ability to successfully integrate multiple components for imaging on a single platform can provide optimal flexibility, mechanical robustness, and resistance to negative environmental factors. Areas of application in astronomical imaging may include spatial filtering of received signals for stellar interferometry and improvement in spectrograph stability⁹⁵.

To date, composite multi-mode waveguide integrated optics devices have been fabricated to examine functionality as a building block structures for slit-reformatting of diffraction-limited spectrographs³³. This can help to overcome challenges associated with slit-width size and coupling efficiency and aid in low-loss reformatting, thus enabling smaller telescopes to perform high-resolution spectroscopic surveys⁹⁶. A proposed device structure known as a “photonic lantern,” can act as a mode-reformatting device to support the conversion of a multi-mode signal into a single-mode signal, thereby translating a see-limited point spread function to a diffraction limited spot. Combining the function of integrated photonics lanterns and slit-formatting techniques, integrated photonics devices could be successfully used in astronomical imaging

⁹² T. Zhang et al. (2013). “Integrated Optical Gyroscope Using Active Long-Range Surface Plasmon-Polariton Waveguide Resonator.” *Scientific Reports*, 4 (3855).

⁹³ L. Guo, B. Shi, C. Chen, and M. Zhao. (2012). “A large-size SiO₂ Waveguide Resonator Used in Integration Optical Gyroscope.” *International Journal for Light and Optics*, 123 (4).

⁹⁴ F. Dell’Ohlio et. al. (2014)/ “Recent Advanced in Miniaturized Optical Gyroscopes.” *Journal of European Optical Sciences*, 9 (14013).

⁹⁵ N. Jovanovic et al. (2012). “Integrated Photonic Building Blocks for Next-Generation Astronomical Instrumentation I: The Multimode Waveguide.” *Optics Express*. Available: <http://arxiv.org/abs/1207.0153>

⁹⁶ J. Bland-Hawthorn and P. Kern (2009). “Astrophotonics: A New Era for Astronomical Instruments.” *Optics Express*, 17 (3).

to take light from the telescope and focusing to a single-mode spectrograph—thereby miniaturizing the size and scale of the imaging system and improving the instrumentation thermal/environmental stability⁹⁷.

The NASA Innovative Advanced Concepts Program has also sponsored a Low-Mass Planar Photonic Imaging Sensor project, which investigated the use of PIC technologies to replace traditional optical telescopes⁹⁸. The Low-Mass Planar Photonic Imaging Sensor was developed from the Segmented Planar Imaging Detector (SPIDER) platform that consists of densely packed white-light interferometers packed onto a PIC structure. Replacing traditional bulk optics necessary for conventional telescopes, the use of the Low-Mass Planar Photonic Imaging Sensor and associated integrated optics can supplant existing technologies at lower costs and required mass/volume. Proposed applications for this device include use as an EO-imager on a Europa mission for high-resolution imaging and remote sensing of changes in planet surface processes³⁶.

IV. Radiation Effects: Developing Reliable Photonic Integrated Circuits for Space-Systems Applications

As the available integrated photonics technology becomes progressively more sophisticated, there is increasing incentive for use in space-systems applications. Photonic integrated platforms that are monolithically integrated are predicted to be robust and to perform well in harsh environments because of their compact nature. With the strong motivating factors for using PIC-based technologies in communications and sensing, as well as the announcement that NASA will be developing the first integrated photonics modem, it is necessary to understand how the performance of these devices is expected to vary in the space environment. Technology development for space applications requires that devices undergo testing of the expected environments, examining the effects of pressure variations, shock/vibrations, extreme temperatures, and exposure to different forms of radiation. While a significant amount of research has been performed to better understand the radiation effects impacting electronic devices, comparatively little is known about the effects of ionizing radiation on integrated photonics devices. To better assess the current state of the field, a literature search has been completed to provide a summary below of previous radiation tests performed on integrated photonics devices, the material platforms of the devices under testing, and subsequent test results.

i. Silica-on-Silicon Arrayed Waveguide Gratings and Silicon-On-Insulator Microphotonic Devices⁹⁹

Radiation testing was performed on commercially available Silica-on-Silicon (SoS) Arrayed Waveguide Gratings (AWGs) and experimental Silicon-on-Insulator (SOI) ring resonator devices operating in the telecom wavelength range; these are both building block structures for optical interconnect communication systems. Of note is the fact that Silicon-on-Insulator devices and building blocks are fabricated using CMOS-processes, which are less sensitive to latch-up effects. Previous testing on bulk optics devices has demonstrated that radiation effects can subsequently result in refractive-index changes and absorption center changes, which have the potential to negatively affect PIC-device performance. In an optical communication system, radiation effects are essential to consider as device failures can result in increased bit-error rates. P. Dumon *et. al* (2005) performed total ionizing dose testing on the aforementioned

⁹⁷ I. Spaleniak, et. al. (2013). “Integrated Photonic Building Blocks for Next-Generation Astronomical Instrumentation: The Multimode to Single-mode Transition. *Optics Express*. Available: <http://arxiv.org/abs/1311.0578>

⁹⁸B. Yoo and R. Scott (2014). “Low-Mass Planar Photonic Imaging Sensor.” *2014 NIAC Symposium*: http://www.nasa.gov/sites/default/files/atoms/files/ben_yoo_nasa_niac_2014_symposium_presentationtagged.pdf

⁹⁹ P. Dumon et. al (2005). “Measured Radiation Sensitivity of Silica-on-Silicon and Silicon-on-Insulator Microphotonic Devices for Potential Space Application.” *SPIE Proceedings: Photonics for Space Environments*.

components using gamma-irradiation up to a total ionizing dose of 300 kRad. Experimental results are summarized in the following table:

| Device Under Testing: | Test Type/Location: | Dose Rate: | Total Dose: | Experimental Results: |
|---|--|-------------|-------------|---|
| 1. SoS Arrayed Waveguide Grating (unpackaged) | TID/ESTEC Co-60 y source (photon energies = 1.173 & 1.332 MeV) | 157 rad/min | 300 kRad | Three transmission channels monitored; Shift measured after radiation testing: 1. Channel 1 shift = 0.03 pm/kRad 2. Channel 2 shift = -0.007 pm/Rad 3. Channel 3 shift = 0.03 pm/kRad |
| 2. SOI ring resonators (unpackaged) | TID/ESTEC Co-60 y source (photon energies = 1.173 & 1.332 MeV) | 82 rad/min | 300 kRad | Transmission to drop port monitored; Linear shift for ring resonator resonant wavelength measured; Shift following radiation testing: 1. Resonator 1: 0.23 pm/kRad 2. Resonator 2: 0.33 pm/kRad 3. Resonator 3: 0.39 pm/kRad |

These interferometric devices are very sensitive to changes in refractive index, which can be caused material defects, one of the reasons why radiation testing of these devices for space-applications is so important. For the SoS arrayed waveguide grating, the transmission spectra of the associated device channels were monitored before radiation, and through the experimental testing up to the total dose of 300 kRad. The resultant measured doses across the three channels were much smaller than the channel bandwidths, suggesting that the SoS components are radiation-hard and would be a good selection for use in optical interconnects. The SOI devices experienced stronger wavelength shifts (approximately one order of magnitude greater) than that seen in the SoS devices, likely due to the fact that SOI waveguides experience a greater sensitivity to any changes in refractive index. However, the order of magnitude of wavelengths shifts here mirror that which would be observed given minor variations in conditions such as temperature and humidity. Additionally, the fact that these devices were tested unpackaged demonstrates that radiation losses for the device are negligible, particularly accounting for the fact that for commercial applications, they would be both packaged and shielded.

ii. Radiation Hardness of Ring Resonators in Silicon Integrated Nano-Photonic Devices¹⁰⁰

Gamma, high-energy electron, and proton tests were performed by R. Ebeleing *et. al* (2010) on PIC-chips containing several different photonic structures with microring resonators and MMI couplers. These devices were tested as representative technologies for integrated nanophotonics sensors, with predicted exposure relevant to radiation environments both in the medical industry and the space industry. The tested devices were fabricated using standard SOI CMOS processes, with summarized results in the following table:

| Device Under Testing: | Test Type/Location: | Dose Rate: | Total Dose: | Experimental Results: |
|---------------------------------------|--|--------------|-------------|---|
| 1. SOI PIC: Chip with ring resonators | Gamma radiation device used: Catharina Hospital, Eindhoven 1 MeV | Not reported | 10 kRad | Ring resonator response measured before and after radiation exposure for 5 ring resonators on PIC chips. Transmission response and FSR remain unchanged within measurement uncertainty. |

¹⁰⁰ R. Ebeleing *et. al* (2010). "Radiation Hardness of Silicon Integrated Nano Photonic Devices." *Proceedings Symp. Of the IEEE Photonics Benelux Chapter, 2010*.

| | | | | |
|---------------------------------------|--|--------------|---|--|
| 2. SOI PIC: Chip with ring resonators | Electron radiation: Radiation Institute Delft (VDG): 1 MeV | Not reported | Fluence exposure range: 10^{12} e-/cm ² through 10^{15} e-/cm ² | Average transmission spectra and FSR falls within experimental fiber coupling error for the device. |
| 3. SOI PIC: Chip with ring resonators | Proton Irradiation: AccTec singletron accelerator (Eindhoven): 1 MeV | Not reported | Tested up to proton fluence of 10^{15} /cm ² | Average transmission dropped as a result of proton sputtering, which results in Si-doping and loss in the PIC structure; FSR decreases with increasing proton fluence. |

The results obtained here for the five ring-resonator based PIC-chips suggest that general functionality of integrated nanophotonics sensors will not be affected up to the assessed fluence levels; however, the devices exposed to increasing levels of proton fluences did experience decays in transmission, on the order of 1.2% per order of magnitude of proton fluence. This suggests that further proton testing may be necessary across different PIC building blocks and associated configurations to understand potential degradation.

iii. Direct, Femtosecond Written Straight Glass Waveguides: Irradiation Tests (2011)¹⁰¹

The motivation for these irradiation tests stemmed from the work involving integrated photonic spectrographs for astronomical imaging. Straight-waveguides were fabricated using a Femtosecond Direct-write laser—a fabrication capability now available at NASA Goddard¹⁰²—onto a transparent dielectric material. Specifically, a Ti: Sapphire laser was used to create the waveguide in an Eagle2000 glass sample. The mode-field diameter (a property which can be used to observe changes in waveguide properties and refractive index contrast) was measured before and after exposure to space environment-like conditions, with the results following radiation tests presented below:

| Device Under Testing: | Test Type/Location: | Dose Rate: | Total Dose: | Experimental Results: |
|---|---|--------------|---|--|
| 1. Straight, femtosecond-etched glass waveguide | 25 kV x-ray radiation from an X-ray Fluorescence Machine | Not reported | Exposed for 200 hrs; difficult to report exact dose for XRF machine, indicated “substantial” dose | No reported change in mode field diameter after exposure |
| 2. Straight, femtosecond-etched glass waveguide | Gamma tank: Co-60 source; energy of gamma-rays not determined | 20 Gy/min | 200 Gy = 20 kRad | No reported change in mode field diameter after exposure |

The preliminary results above indicate that directly written integrated photonic waveguides are not sensitive to degradation from gamma/x-ray radiation, which is promising for use space-based applications.

iv. InP Mach-Zehnder Modulator: Irradiation Tests (2013)¹⁰³

Detectors that are used to perform experimental work in High Energy Physics must be able to retain full functionality in high-radiation environments. Examples of such high-radiation environments include those in the experiments for the Large Hadron Collider at CERN, where at a distance of a few mm from the beam,

¹⁰¹ N. Jovanovic et. al (2011). “Prospects for Integrated Photonics in Space Applications.” *ACOFT Presentation, IQEC/CLEO Pacific Rim*.

¹⁰² M. Krainak and S. Merritt (2016). “Photonic Integrated Circuits: NASA Goddard Space Flight Center.” Available: <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160004055.pdf>

¹⁰³ D. Gajanana et al. (2013). “Irradiation Tests on InP-based Mach-Zehnder Modulator.” *Topical Workshop on Electronics for Particle Physics, 2012*.

an expected total ionizing dose would be on the order of several hundred MRad. This work was completed by D. Gajana *et. al* (2013) to assess the radiation hardness performance of Oclaro's Indium Phosphide based Mach-Zehnder Modulators, devices that are also relevant to detection/communication systems in space systems. Stepwise proton irradiation was performed at the CERN IRRAD-1 facility (24 GeV/c proton beam); however, improper handling of devices following irradiation at fluences of 10^{12} , 10^{12} , and 10^{12} protons/cm² meant that only one data point was collected at 10^{15} /cm². At this highest fluence level, the MZM modulation response was almost completely absent. Direct modulation of lasers can be difficult to achieve under harsh space radiation environments, which means that it is important to explore functional alternatives both for high energy physics experimental work and for use in space systems. Nevertheless, further testing must be performed to understand the effects of proton radiation on InP PIC devices, and specifically, the modulation response of MZM devices. To date, no further work has yet been reported in this area of study.

v. Radiation Hardness of High-Q Silicon Nitride Micro-resonators¹⁰⁴

Radiation-induced changes of optical properties and associated loss have not been extensively researched for Silicon Nitride (SiN) integrated photonics. In this irradiation tests, Brasch *et. al* (2014) investigated the radiation hardness of SiN waveguide resonators embedded in silicon dioxide cladding, with corresponding quality-factors of $\sim 10^6$. The structure of these devices are relevant for use in sensing and communications, and as optical frequency comb generators and optical filters.

Proton irradiation tests were completed at the Paul-Scherrer Institute in Switzerland (PSI), and it is necessary to note that shipping between PSI and the research facility where the devices were characterized presented challenges in assessing any short-term radiation induced loss. The tests here were the first to assess the effect of proton radiation on the Q-factor as a measure of SiN resonator radiation hardness. The Q-factor is dependent on the linewidth of the resonator, and this quantity was measured throughout the radiation tests, as presented in the table below:

| Device Under Testing: | Test Type/Location: | Dose Rate: | Total Dose: | Experimental Results: |
|---|---|--------------|--|---|
| 1. SiN waveguide resonator embedded in SiO ₂ | Proton Irradiation: Paul-Scherrer Institute, Switzerland; Irradiated at four energy levels: 18.3, 30.7, 61.6, and 99.7 MeV | Not Reported | Fluences Used (protons/cm ²): 1. 6.0000×10^{10} 2. 4.004×10^{10} 3. 1.416×10^{10} 4. 1.516×10^{10} | Slight deviation in linewidths, (on the order of 1%), no degradation of Q-factor. |

The results presented here show that high-energy proton radiation did not cause degradation of the Q-factor ($\sim 10^6$)—a parameter important for relevant uses in space applications, such as optical frequency combs—for SiN microring resonators. These results could be extended to make inferences about performance characteristics of other SiN PIC building blocks, such as SiN straight waveguides for use in high-radiation environments. Another example of a SiN PIC structure, the Photonic Biosensor for Space Applications (PBSA) discussed in Section III, consisting of a SiN ring resonator and associated microfluidics structure was also tested using high energy protons and reported that no changes in performance were observed¹⁰⁵.

¹⁰⁴ V. Brasch *et. al* (2014) "Radiation Hardness of High-Q Silicon Nitride Microresonators for Space Compatible Integrated Optics." *Optics Express*. Available: <http://arxiv.org/pdf/1406.0297.pdf>

¹⁰⁵ S. Pantoja, *et. al* (2014). "Integration Of an Optical Ring Resonator Biosensor Into a Self-Contained Microfluidic Cartridge Including Active, Single-Shot Micropumps." *Congrex Projects*. Available: <http://www.pbsa-fp7.eu/>

vi. Silicon Photonics for Data Links: Mach-Zehnder Interferometer Silicon Modulator¹⁰⁶

As detailed in section iv., radiation effects that affect optical components are also of concern in high energy particle physics experiments at CERN's Large Hadron Collider. Integrated photonics devices offer solutions for use as optical components in these environments because they can serve as optical links to send timing and control signals; they have the high bandwidth necessary to rapidly read out data from particle detectors; and it is expected that they can withstand high levels of radiation without performance degradation. CERN has previously developed integrated optics "versatile-link" transmitters based on III-V semiconductor materials that are able to withstand total ionizing doses of up to 1000 kRad (a figure which they cite as nearly 10,000 times more than the exposure of electronic components on the Apollo missions). Looking ahead to assess technology for use in the high-luminosity Large Hadron Collider, CERN has begun exploring Silicon Integrated photonics devices as replacement of III-V components, in attempts to increase component radiation harness and system data rates. The ability to fabricate Silicon PIC structures with CMOS techniques and the ease of integration with existing Si electronic is also a strong motivating factor. To begin assessment of Silicon integrated photonic devices for use in applications relevant to CERN radiation environments—in which total doses of 50,000 kRad are expected over 10 years of operation—neutrons and x-rays irradiation tests were performed on high-speed Mach-Zehnder interferometer Silicon modulators¹⁰⁷. The subsequent results of these two tests are presented in the following table:

| Device Under Testing: | Test Type/Location: | Dose Rate: | Total Dose: | Experimental Results: |
|--|---|--|----------------|---|
| 1. Mach-Zehnder Interferometer (Si modulator) – 2 devices under test | Neutron irradiation test at the Cyclotron Resource Center in Louvain-La-Neuve | Exposed to a fluence of 1.2×10^{15} n/cm ² over a period of 16 hrs | TID: 1000 kRad | A. Leakage Current: Measured increase in leakage current in devices under testing (22 nA); partial recovery of leakage current B. Modulation Efficiency: Small Shift in transmission observed at all bias voltages, but device continues to modulate |
| 2. Mach-Zehnder Interferometer (Si modulator) – 2 devices under test | X-Ray Irradiation: X-Ray Irradiation System at CERN; peak energies = 10 keV | 110 kRad/min | TID: 1.3 MGy | A. Leakage Current: Measured increase in leakage current in devices under testing (12 nA); partial recovery of leakage current B. Modulation Efficiency: No longer operational after exposure to total dose. |

From these results, it is clear that the device degrades after successive dose-level x-ray exposures, and at higher dose levels, the device can no longer operate as a modulator, demonstrating strong degradation when exposed to ionizing radiation. The TID dose levels here are quite high, and so additional work is necessary to translate the understanding of degradation mechanisms for use in space-flight applications. Additionally exploration for potential low-dose-rate effects is also recommended to identify modulator sensitivity and improve overall radiation resistance. Further investigations have been completed attempting to improve radiation hard designs for Si-based Mach-Zehnder interferometers for use in environments where very high TID levels (~1 MGy) are expected; however, at this time, designs resistant to these levels has not yet been fabricated. Techniques for improving radiation-hardness in Si-based MZM devices can

¹⁰⁶ M. Zeiler. (2015). "CERN'S LHC Explores Silicon Photonics for Data Links." *SPIE Professional*. Available: https://spie.org/membership/spie-professional-magazine/spie-professional-archives-and-special-content/spie-professional-archives/archived-issues/2015_oct_archive/silicon-data-links-at-cern-lhc

¹⁰⁷ S. Seif El Nasr-Storey, et. al. (2015). "Effects of Radiation on a Mach-Zehnder Interferometer Silicon Modulator for HL-LHC Data Transmission Applications." *IEEE Transactions on Nuclear Science*, 62 (1).

include increased doping levels in the device phase shifting diode and increasing thickness of device slab, which has been successfully modeled such that expected 1 MGy doses would not affect simulated phase-shifts¹⁰⁸. Improvements such as increasing the average concentration of free carriers of the slab region can help to mitigate the effects of ionizing radiation; though flight systems will likely not encounter the same dose profiles, these design parameters can be used for optimal radiation-hard device structures for space-applications.

vii. Continued Investigations of Radiation Effects on Silicon Integrated Photonic Components:

The majority of most recent investigations (2015) related to the effects of radiation on integrated photonics building blocks and devices have been focused on continued evaluation of Silicon-based materials. Additional gamma irradiation testing has been completed on SOI microring resonator waveguide structures and on polymer assisted amorphous silicon ring resonators, as detailed in the following table:

| Device Under Testing: | Test Type/Location: | Dose Rate: | Total Dose: | Experimental Results: |
|--|--|-----------------------|---|---|
| 1. Silicon-on-Insulator (SOI) Waveguide Microring Resonator ¹⁰⁹ | Uniform exposure in an irradiator cell containing a Co-60 source, with gamma-energies of 1.17 MeV and 1.13 MeV | Not reported | Dose Increments: 2 mRad and 35.6 mRad | An SOI ring resonator with a 20 micron radius was used for testing. The waveguide group index was measured prior to irradiation and following each subsequent irradiation step. The measured group index changes at the total dose of 35.6 mRad were on the order of 10^{-3} corresponding to refractive index changes of 10^{-5} (exhibits resistance to gamma radiation.) |
| 2. Polymer-Assisted Amorphous Silicon Racetrack Ring Resonators ¹⁰⁹ | Uniform exposure in an irradiator cell containing a Co-60 source, with gamma-energies of 1.17 MeV and 1.13 MeV | Not reported | Dose Increments: 1, mRad, 3 mRad, 7 mRad, and 10 mRad | Polymer assisted amorphous silicon racetrack ring resonators were assessed for thermos-optic sensitivity changes prior to radiation and following each subsequent radiation step. A wavelength shift of the TO sensitivity curve was determined to be -8 pm/K after exposure to radiation, indicating that the radiation is likely breaking chemical bond in the polymers. |
| 3. Silicon-on-Insulator Microring Resonators: Unpassivated and Passivated Ring Structures ¹¹⁰ | Irradiated with 662-keV Cs-gamma rays and 10 keV x-rays (using an ARACOR model 4100 Tungsten source) | Varied across testing | Gamma TID: 147 kRad (SiO ₂) X-Ray TID Dose Increments: 145, 870, 1341, 6705 (krad (SiO ₂)) | Transmission spectra of ring resonators passivated with native oxide were immune to changes at the tested dose levels. The radiation testing of unpassivated ring structures resulted in a transmission blue-shifts, with a resonance shift dependent on dose increment until an approached saturation level. Indicated radiation harness for passivated silicon ring resonators (accounting for temperature fluctuations). |

¹⁰⁸ S. Seif El Nasr-Store, et. al (2015). "Modeling TID Effects in Mach-Zehnder Interferometer Silicon Modulator for HL-LHC Data Transmission Applications." *IEEE Transactions in Nuclear Science*, 62(1).

¹⁰⁹ V. Singh. (2015). "Chalcogenide Glass Materials for Integrated Infrared Photonics." Available: <https://dspace.mit.edu/bitstream/handle/1721.1/101459/940569218-MIT.pdf?sequence=1>

¹¹⁰ S. Bhandaru, et. al. (2015). "Total Ionizing Dose Effects on Silicon Ring Resonators." *IEEE Transactions on Nuclear Science*, 62 (1).

The above gamma irradiation tests of SOI structures present further evidence of the radiation hardness of standard silicon building blocks when exposed to relevant dose levels for space systems applications. All radiation testing to-date of PIC building block components in silicon and indium phosphide indicates that—with appropriate measures to control for temperature fluctuations—integrated optics device performance will not be affected by harsh radiation environments expected in space missions. However, while existing radiation hardness appears very promising for space flight applications there remain numerous avenues for exploration to better understand the impact of radiation effects on integrated photonics circuits. The majority of radiation effects testing that has been completed at this time has been performed on silicon integrated photonics devices that have been fabricated using conventional CMOS techniques.

To date, there exists minimal data on indium phosphide PIC structures, and further investigation is needed to understand the performance of indium phosphide building blocks seen on both the standard JePPIX runs and those in custom project designs. The range of device building block structures that have been tested is also limited, and the majority of tested device structures involve microring resonators. Characterization of performance of active PIC building blocks such as lasers and SOAs for indium phosphide PICs or heterogeneous devices following radiation tests has not been performed.

Uncertainties pertaining to radiation effects in integrated photonics involve the following research areas: comparison of radiation-hardness across all PIC materials platforms, performance of multiple integrated structures on chip, comparison of packaging types and subsequent result on radiation hardness, and process variations across foundry runs that affect radiation hardness. Though integrated photonics devices on silicon and indium phosphide platforms are radiation tolerant at doses anticipated for use on NASA missions, degradation of device performance has been observed when tested for functionality in high-energy physics testing environments like those expected at CERN’s high-luminosity Large Hadron Collider. The effects of radiation on the performance of integrated photonics structures (particularly InP)¹¹¹ remain an active area of research investigation¹¹², and a better understanding of degradation mechanisms will allow for the improvement of radiation tolerant integrated PIC designs in all expected radiation environments.

¹¹¹ Photon Integration Group, Technical University of Eindhoven. (2016) “Photonic Readout Circuits.” Available: <https://www.tue.nl/en/university/departments/electrical-engineering/research/research-groups/photonic-integration-phi/research/photonic-readout-circuits>

¹¹² J. Hu. (Scheduled Presentation in November 2016). “Radiation Effects in Integrated Photonics and Nano-Opto-Mechanical Systems.” *AVS 63RD International Symposium and Exhibition*.